Have the Elusive Progenitors of Supernovae Type Ia Been Discovered?

Mario Livio and Adam Riess

Space Telescope Science Institute
3700 San Martin Drive
Baltimore, MD 21218
email: mlivio@stsci.edu; ariess@stsci.edu

ABSTRACT

The recent detection of Hα emission in the supernova Type Ia SN 2002ic could be taken to mean that the elusive progenitor systems of Type Ia supernovae have finally been identified. At first glance, the observation appears to support a single-degenerate scenario, in which the white dwarf accretes from a normal companion. In this Letter we show that the opposite may be true, and the observations may support the merger of two white dwarfs as the cause for Type Ia supernovae.

Subject headings: cosmology: observations – supernovae: general

1. Introduction

The recent detection of Hα emission in the spectrum of the supernova Type Ia (SN Ia) SN 2002ic (Hamuy et al. 2003) is a landmark discovery. While there is very little doubt that SNe Ia represent the thermonuclear disruption of mass accreting white dwarfs (WDs), the precise nature of the progenitor systems remains uncertain (Branch et al. 1995; Livio 2001). Given that SNe Ia are the tool of choice for confirming the acceleration of cosmic expansion (Riess et al. 1998; Perlmutter et al. 1999), the importance of identifying the progenitors cannot be overemphasized. The two main scenarios that have been proposed involve either the merger of two white dwarfs (the double-degenerate scenario; Iben & Tutukov 1984; Webbink 1984), or a single white dwarf accreting from a normal companion (the single-degenerate scenario; Whelan & Iben 1973; Nomoto 1982). Recently it has been argued theoretically, that single-degenerate progenitors are favored (even though it is very difficult for hydrogen-accreting WDs to reach the Chandrasekhar limit; Piersanti et al. 2000), and that double WD mergers may lead to accretion-induced collapses rather than to SNe Ia

(Livio 2001; Nomoto et al. 2000). The tentative discovery (if confirmed) of an enhanced SN Ia rate near jets in active galactic nuclei (Livio, Riess, & Sparks 2002; Capetti 2002) appears to support this conclusion. Nevertheless, until SN 2002ic the "smoking gun"— the presence of hydrogen in the spectrum—was missing. The clear detection of a broad (FWHM $\sim 1800 \ \text{km s}^{-1}$) H$\alpha$ component in SN 2002ic appears on the face of it to demonstrate that at least some SNe Ia result from single-degenerate progenitors. In the present letter we show that this conclusion may be *premature*.

2. Why Now?

One of the key questions posed by the observations of Hamuy et al. (2003) is: Why was hydrogen not detected before? This becomes particularly puzzling when we realize that there exist about 100 spectra of SNe Ia in which a signature of the strength of that seen in SN 2002ic would have been detected (T. Matheson, private communication), had it been there. In fact, Hamuy et al. noted that the amount of shock-heated circumstellar material needed to produce the observations of SN 2002ic is totally unexpected for a SN Ia. Accordingly, they suggested that the progenitor system was a binary consisting of a C/O white dwarf and a *massive* (3–7 M$_\odot$) asymptotic giant branch (AGB) star. The presence of the latter was necessitated by the need to have an integrated circumstellar mass of at least a few solar masses.

The main problem with this scenario is that one would expect to observe *a range* of strengths of Hα lines in SNe Ia, depending on the amount of circumstellar material (in turn, determined primarily by the mass of the AGB star), rather than *detecting a relatively strong line in one case only* (it is also hard to believe that this is the first progenitor system containing an AGB star).

We propose instead that the total absence of Hα lines in all the pre-SN 2002ic SNe Ia observed to date argues that SN 2002ic represents rather rare circumstances, and *not* a white dwarf accreting from the wind of an AGB star.

3. A Supernova Ia in a Common Envelope?

All the evolutionary scenarios leading to the formation of close double white dwarf systems involve a stage in which an AGB star fills its Roche lobe and transfers mass onto a white dwarf companion (e.g. Yungelson & Livio 2000). Under these conditions, the mass transfer process is unstable, and the system evolves rapidly into a common envelope (CE)

configuration, inside which the white dwarf and the core of the AGB star spiral-in (e.g. Rasio & Livio 1996; Taam & Sandquist 2000). Typically, the CE phase lasts a few hundred to a few thousand years, and results in the ejection of the envelope and the emergence of a double white dwarf system (e.g. Sandquist et al. 1998; Taam & Sandquist 2000 and references therein). I propose that SN 2002ic represents one of those rare cases in which the explosion occurs *during* (or immediately following) the CE phase, and in which some part of the envelope has not been previously ejected. This raises two immediate questions: (i) Is this possible at all? and (ii) Does this support a single-degenerate or a double-degenerate scenario?

For the white dwarf to actually reach the Chandrasekhar mass via accretion of hydrogen-rich material during the CE phase is extraordinarily unlikely. Steady burning occurs for a narrow range of accretion rates of order (Paczyński & Żytkow 1978; Nomoto, Nariai & Sugimoto 1979; the limits are determined: at the low end by the requirement that the pressure at the time of ignition be sufficiently low to prevent a shell flash, and at the high end by the accretor expanding to supergiant dimensions)

$$0.4 \, \dot{M}_{\mathrm{RG}} \lesssim \dot{M} \lesssim \dot{M}_{\mathrm{RG}} \quad . \tag{1}$$

Here $\dot{M}_{\mathrm{RG}}$ is the rate at which the white dwarf expands to giant dimensions and is given by

$$\dot{M}_{\mathrm{RG}} \simeq 8.5 \times 10^{-7} (M_{\mathrm{WD}}/\mathrm{M}_\odot - 0.52) \, \mathrm{M}_\odot/\mathrm{yr} \quad . \tag{2}$$

Even assuming that the accretion rate could be regulated to the rate given by equation (1) [most likely it would settle on the Eddington rate of $\dot{M}_{\mathrm{EDD}} \simeq 1.7 \times 10^{-5} (R_{\mathrm{WD}}/10^9 \, \mathrm{cm}) \, \mathrm{M}_\odot/\mathrm{yr}$ at which mass would not be retained], the WD would increase in mass by at most $\sim$0.001 M$_\odot$ during the CE phase. This would require the WD to be within 0.001 M$_\odot$ of the Chandrasekhar mass upon entering the CE—a very unlikely situation, even taking into account the rarity of Hα detection (e.g. only 2 out of a sample of 130 WDs were found to have masses higher than 1.2 M$_\odot$; Bergeron, Saffer, & Liebert 1992; although see Hachisu & Kato 1999).

A second possibility is that the WD spirals-in all the way to the center and merges with the AGB star's core. Interestingly, a scenario for SNe of similar type was suggested almost 30 years ago by Sparks & Stecher (1974), but has long since been discarded due to the absence of hydrogen in the spectra. What I propose here is that the spiraling-in process unbinds most, but not all of the envelope, so that coalescence becomes inevitable. At the time of merger, most of the envelope will be at a distance of

$$d \simeq 3 \times 10^{15} \left(\frac{V}{10 \, \mathrm{km \, s^{-1}}} \right) \left(\frac{\tau_{\mathrm{CE}}}{100 \, \mathrm{yr}} \right) \, \mathrm{cm} \quad . \tag{3}$$

from the core. Here V is the ejection velocity and τ_{CE} is the duration of the CE phase. The condition for a merger to occur (as opposed to ejection of the entire envelope and the

formation of a binary WD system) is given by the requirement that the binding energy of the CE be larger than the gravitational energy available from orbital shrinkage (Livio 1996; deKool 1990)

$$\frac{M_{\mathrm{AGB}}(M_{\mathrm{AGB}} - M_C)}{\lambda\, a_0\, r_L} > \alpha_{\mathrm{CE}} \left(\frac{M_C M_{\mathrm{WD}}}{2R_C} - \frac{M_{\mathrm{AGB}} M_{\mathrm{WD}}}{2a_0} \right) \quad . \tag{4}$$

Here a_0 is the initial separation, r_L is the Roche lobe radius of the AGB star (in units of the separation), M_C and R_C are the mass and radius of the core, respectively, α_{CE} is the CE efficiency parameter (Livio & Soker 1988; Iben & Tutukov 1984), and $\lambda \sim 0.5$ depends on the stellar density profile. The value of α_{CE} is not known even to within a factor 10 (e.g. Livio 1996). However, for reasonable values ($\alpha_{\mathrm{CE}} \sim 0.1$–1) condition (4) requires relatively massive AGB stars [since the condition can be approximated as $(M_{\mathrm{AGB}}/M_{\mathrm{WD}})^2 \gtrsim 1/8\, \alpha_{\mathrm{CE}}(a_0/R_C)$; and $a_0/R_C \sim 10^4$] and can be expected to be satisfied only in a fraction of a percent of all systems (e.g. Yungelson & Livio 1998). The observed Hα emission would result from the interaction of the explosion with the previously-ejected envelope. This would be consistent with the rarity of Hα detections. Most importantly, however, if this scenario is correct, the Hα detection by Hamuy et al. *results from a double-degenerate scenario*!

4. Conclusions

One might have thought that the detection of hydrogen in the spectrum of a SN Ia would have finally revealed the elusive progenitor to be a single-degenerate system. In this Letter we suggest that this may not be the case. Paradoxically, the Hα detection could result from a double-degenerate scenario! To be sure, the actual result of the merger process remains as uncertain as ever, and it may lead to an accretion-induced collapse rather than to a SN Ia. Other exotic possibilities, such as the explosion of the core of an AGB star ("type 1.5" event; Iben & Renzini 1983) may exist (as already suggested by Hamuy et al. 2003). However, the latter would require some other mechanism to place (at least a part of) the envelope at $\sim 10^{15}$ cm. Future, more sensitive, observations will reveal whether the detection of Hα is a very rare, but relatively clear event, or whether a range of line strengths is detected. The latter case would clearly support a single-degenerate interpretation.

REFERENCES

Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228

Branch, D., Livio, M., Yungelson, L. R., Boffi, F. R., & Baron, E. 1995, PASP, 107, 717

Capetti, A. 2002, ApJ, 574, L25

deKool, M. 1990, ApJ, 358, 189

Hachisu, I. & Kato, M. 1999, ApJ, 517, L47

Hamuy, M., et al. 2003, Nature, in press

Iben, I. Jr. & Renzini, A. 1983, AR&A, 21, 271

Iben, I. Jr. & Tutukov, A. V. 1984, ApJS, 54, 355

Livio, M. 1996, in Evolutionary Processes in Binary Stars, eds. R. A. M. J. Wijers, M. B. Davies, & C. A. Tout (Dordrecht: Kluwer), 141

Livio, M. 2001, in Supernovae and Gamma-Ray Bursts (Cambridge: Cambridge University Press), 334

Livio, M., Riess, A., & Sparks, W. 2002, ApJ, 571, L99

Livio, M. & Soker, N. 1988, ApJ, 329, 764

Nomoto, K., Nariai, K., & Sugimoto, D. 1979, PASJ, 31 287

Nomoto, K., Umeda, H., Kobayashi, C., Hachisu, I., & Tsujimoto, T. 2000, in AIP Conf. Proc. 522, Cosmic Explosions, ed. S. S. Holt & W. W. Zheng (Melville: AIP), 35

Paczyński, B. & Żytkow, A. N. 1978, ApJ, 222, 604

Perlmutter, S., et al. 1999, ApJ, 517, 565

Piersanti, L., Cassisi, S., Iben, I. Jr., & Tornambé, A. 2000, ApJ, 535, 932

Rasio, F. A. & Livio, M. 1996, ApJ, 471, 366

Riess, A. G., et al. 1998, AJ, 116, 1009

Sandquist, E. L., Taam, R. E., Chen, X., Bodenheimer, P., & Burkert, A. 1998, ApJ, 500, 909

Sparks, W. M. & Stecher, T. P. 1974, ApJ, 188, 149

Taam, R. E. & Sandquist, E. L. 2000, ARA&A, 38, 113

Webbink, R. F. 1984, ApJ, 227, 355

Whelan, J. & Iben, I. Jr. 1973, ApJ, 186, 1007

Yungelson, L. & Livio, M. 1998, ApJ, 497, 168

Yungelson, L. & Livio, M. 2000, ApJ, 528, 108